

EVOLUTION OF LIGHTING: FROM THE EARLY DAYS OF PUBLIC LIGHTING TO SMART CITIES - REVIEW

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The advancement of lighting technology is one of the most significant innovations in the history of civilization, reflecting humanity's ongoing effort to conquer darkness. From early natural light sources, such as fire and oil lamps, to modern, energy-efficient artificial lighting—like incandescent bulbs, fluorescent tubes, and LEDs—lighting has profoundly influenced our ways of living, working, and interacting in society. This paper reviews the evolution of lighting technology, closely examining its relationship with scientific and technological progress as well as socio-economic changes. It highlights crucial milestones in the history of lighting, the emergence of various light sources, their operation, and their overall impact on society. Special attention is given to the social, economic, and environmental impacts of lighting technology, as well as future trends. The analysis encompasses the advantages and disadvantages of various light sources, taking into account future perspectives for lighting technology, particularly in terms of energy efficiency and sustainability. It also explores potential future developments in smart lighting and its applications.

Keywords: lighting technology, history of light sources, social impact, energy efficiency

1. Introduction

In today's world, being surrounded by artificial light is a common experience, but this has not always been the case. This study examines street lighting and its potential effects on our lives. First, it is important to define public lighting. As the name suggests, public lighting is intended to serve the common good and benefit all members of a community. Thus, these lights are not installed on private property without permission or in areas where their installation is opposed by the public. Instead, they are placed in locations that are accessible to and frequented by many people. The primary purpose of public lighting has always been to enhance safety by improving visibility, a goal that has remained consistent over time [1]. Street lighting can have a significant psychophysical effect on perceived safety. Several studies indicate that thieves and violent offenders tend to avoid well-lit areas rather than commit crimes in darker, unlit places. In well-lit areas, there is a greater likelihood that someone will witness a crime, increasing the chances of identifying the perpetrator. Conversely, even if someone is nearby in a darker space, identifying the perpetrator is more difficult. This awareness may contribute to the deterrent effect of well-lit environments. Moreover, numerous studies demonstrate the importance of street lighting in reducing accidents. Hazardous road

sections must have adequate lighting. Proper lighting can highlight potential hazards while ensuring that it does not adversely affect road users, for example, through glare or excessive brightness.

2. Research methodology

This section provides a brief overview of the research topic, highlighting its significance and the research questions addressed. The investigation outlines the theoretical framework and general methodology underlying the study.

The literature review provides a comprehensive historical analysis of the evolution of lighting technologies, tracing their development from prehistoric times to the present. It includes an extensive examination of key technological advancements, such as incandescent bulbs, fluorescent tubes, and LED lights.

Additionally, the study investigates the socioeconomic impact of lighting technology. Specifically, it explores the economic and social implications of lighting innovations, focusing on energy consumption and human-centered design. Recent advancements in lighting technology, including intelligent lighting systems, are examined from an Internet of Things (IoT) perspective, with an emphasis on future trends.

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The research is based on information obtained from both the literature and online sources. A literature review conducted using the PRISMA methodology [2] focused on previously published articles on the history of lighting development. Simultaneously, various databases, public historical knowledge bases, websites of experts and researchers in the field, and archival materials were examined.

3. Significant milestones in the history of artificial lighting

3.1. Prehistory and ancient past: Fire, the beginnings

The demand for street lighting is not a modern concept; it dates back to ancient Greece and Rome, though it differed significantly from what we have today. One significant difference is that electricity was unavailable in ancient times, so lighting technology relied on other sources, such as torches and candles [3]. Additionally, in ancient times, street lighting was primarily for individual use rather than for the public.

In ancient Athens, wealthy citizens would hire slave boys to carry lanterns or torches to light their paths, providing safety when navigating stairs, for example. This type of lighting was not widely accessible, as not everyone owned enslaved individuals, and such lighting was sporadic. The cost of torches or lanterns also meant that darkness enveloped many streets after sunset.

In ancient Rome, street lighting primarily consisted of soldiers patrolling at night with torches, allowing them to spot potential crimes. Unlike today's fixed street lamps, ancient lighting sources were mobile, moving with the person needing light [4].

Later on, it became common for Romans to illuminate their villas and the surrounding areas using oil lamps, operated by specific enslaved people known as lanternarii [4]. This lighting method persisted for a long time without significant technological advancements, continuing through the Middle Ages and lasting until the 19th century.

3.2. Medieval and pre-industrial times

In medieval London, "link boys" were employed in the evenings to escort individuals from one place to another by lighting the way with torches [4].

In the pre-industrial era, London and Paris stood out as two of the most advanced societies of that time. Urbanization and the pursuit of a more civilized lifestyle were major driving forces in these cities, fostering technological development and creating demand for new solutions. Although London already had non-stationary lighting that benefited specific individuals or groups, primarily those who utilized the services of "link boys", street lighting serving the public interest also existed from the 16th century [5]. However, this early public lighting was not widespread; it mainly covered the well-frequented areas of developed cities such as London and

Paris and was limited to a few main streets. Consequently, link boys remained in demand for some time.

It is also important to note that the primary lighting source was fire, requiring lamplighters to go out each night to ignite the lamps individually. The continuous increase in the number of street lighting fixtures in major cities demonstrates the growing need for public lighting. By the 1700s, nearly 3,000 streetlamps had been installed in Paris [6].

A noticeable difference between modern streetlamps and these historical fixtures is that the old lamps were designed almost as works of art, standing out from the streetscape and drawing attention. In contrast, today's modern streetlamps aim to be inconspicuous, blending into the environment.

According to Paris police records [6], vandalism and theft of street lamps have been ongoing issues since their introduction. A primary reason for this may be that illuminated streets hindered the nighttime activities of specific individuals, indicating that lighting has a deterrent effect on particular crimes.

Interestingly, in the 16th to 18th centuries, property owners in Paris with windows facing streets or alleys were required by decree to hang lanterns from their windows each night. Failure to comply could result in a penalty of one shilling.

The next significant advancement in street lighting came in 1745, when an improved oil lamp, known as the "réverbère" was introduced in Paris. The term is derived from the French word for "réverbération" [7]. This new lamp featured a polished mirror behind the flame, which concentrated and amplified the emitted light. These lamps were considerably brighter than their predecessors, leading to complaints from some residents.

At this time, Europe was on the brink of the Industrial Revolution, which would significantly accelerate technological development, including advancements in public lighting.

3.3. Gas lamp, a classic

The next significant milestone in the technological development of public lighting was the advent of gas lamps. This milestone was important because it represented a departure from the lighting technologies used since ancient times, such as torches and oil lamps. Gas lamps were the first type of lighting that could be widely adopted, extending public lighting beyond the more developed cities.

The development and introduction of gas lamps occurred during the Industrial Revolution, and the history of this technology is considerably more complex than that of its predecessors, which primarily relied on oil for light. There was a substantial demand for public lighting from citizens, as evidenced by the growing number of newly installed lamps. However, the rise of gas lamps was also a response to the limitations of oil lamps, which often failed to provide satisfactory light output on the darkest nights. The most advanced oil lamps of the time, known as réverbère lamps [7], produced a moderate

luminous flux capable of illuminating small areas. Nevertheless, they were inefficient and not sufficiently energy-efficient for broader use.

In contrast, gas lamps generate light by igniting gas instead of oil. The major technological challenge of these lamps lay in developing the materials responsible for light emission, as the overall structure remained unchanged [8]. Early gas lamps operated using coal gas [9], a substance whose history dates back to 1726 and is linked to the work of Stephen Hales. Hales was the first, as confirmed by publications, to artificially create a flammable gas from coal distillation [10]. Born on September 17, 1677, in Bekesbourne, England, Hales trained as a theologian but was deeply interested in mathematics, chemistry, physics, biology, and botany. His contributions to these fields made him well-known. Hales' findings on coal distillation and other significant observations and measurements were documented in his article [10]. His work was first mentioned in the "Philosophical Transactions of the Royal Society" journal in 1733. The article discussed the properties of the gas he created, including its flammability [11]. Founded in 1665, this journal was the first in the world dedicated to scientific inquiries and has featured famous figures such as Sir Isaac Newton, Benjamin Franklin, Charles Darwin, James Clerk Maxwell, and Stephen Hawking. The publication of Hales' discovery in this journal marks a significant recognition of his work.

In 1735, another article appeared in the same journal, titled "VI. A Chemical Experiment by Mr. John Maud, Demonstrating the Phenomenon of the Inflammable Air Shown to the Royal Society by Sir James Lowther, Bart." This article reported on an experiment involving the gas [12].

William Murdoch was the first to explore the practical applications of gas for lighting. Born in 1754 in Lugar, Scotland, Murdoch began his career as a mechanical engineer. His talent was quickly recognized, and he proposed many innovative ideas, including a high-pressure steam engine, which was ultimately rejected by James Watt and his partner, Matthew Boulton [13].

Murdoch is best known for developing a gas lamp that he conceived while smoking a pipe. When he placed coal dust in the pipe's bowl [14], it ignited and produced gas that flowed through the pipe's stem. He observed how brightly it glowed and realized the gas could be harnessed for lighting. He then created a hand lantern that operated using gas, employing a bladder to store the gas and a tube to connect it to a nozzle. He was pleased with his invention, and by 1797, he had implemented the technology in his home and workshop. In 1798, he illuminated the main building of the Soho Foundry using his gas lamp [15]. In 1806, Murdoch presented his findings on the use of gas from coal for economic purposes to the Royal Society, for which he received the Count Rumford Gold Medal for his discovery and writing [16]. Meanwhile, interest in Murdoch's practical application of gas lighting grew among industry leaders and inventors [13]. The first well-documented instance of street lighting using gas lamps is attributed to the German inventor Frederick Albert Winsor. He was the first to

patent gas-lamp lighting in 1804, and on January 28, 1807, he demonstrated his gas lamp for public lighting in Pall Mall, London [17]. A significant milestone in public lighting occurred on December 31, 1813, when London's Westminster Bridge was illuminated with gas lamps [18]. After London, Preston in Lancashire became the first city in England to install a gas lamps in 1816. The Preston Gaslight Company subsequently introduced a newly improved and brighter lamp [19].

In 1817, Glasgow's Gas Light Company was founded, and on September 15, 1818, it activated its first streetlights in Glasgow. Despite insurers in Glasgow threatening to raise prices if property owners installed gas-powered lights—due to concerns about explosion risks, this did not hinder the technology's growing popularity.

Gas lamps spread beyond England, gaining popularity due to their cost-effectiveness compared to previous lighting solutions. In the United States, the first gas-powered streetlamps were installed in Baltimore on February 7, 1817, and they still stand as memorials at North Holliday Street and East Baltimore Street.

In Paris, gas lighting was introduced in January 1829 on major streets, including the Place du Carrousel, Rue de Rivoli, Rue de la Paix, Place Vendôme, and Rue de Castiglione. These lights continued to expand throughout Paris, leading to the city being called the "City of Lights" [20].

However, street lighting was not universally available at that time. For instance, in New Zealand, gas lamps were first installed in the 1860s, whereas many other cities introduced street lighting even later. It is also notable that while much of this discussion focuses on the Western world, historical records indicate that the Chinese used natural gas for lighting as far back as 500 BC, an impressive development considering that only torches were known elsewhere at that time.

In Russia, gas lamps were developed mainly due to the efforts of retired Lieutenant Pyotr Sobolevsky. In 1811, French engineer Philippe le Bon improved the "thermo-lamp" and presented it to Emperor Alexander I, who assigned him the task of planning the lighting of St. Petersburg with gas lamps. However, Napoleon's invasion of Russia in 1812 delayed this project, and it was not until 1819 that the first gas-powered streetlamp was illuminated on Aptekarsky Island in St. Petersburg. On September 27, 1839, 204 gas lamps were ceremonially turned on in the city. The new technology quickly gained popularity, and by the mid-19th century, many main buildings and streets in St. Petersburg were equipped with gas lamps [21].

Meanwhile, coal gas faced competition from oil gas, known as naphtha or petroleum ether. Naphtha is a flammable and volatile hydrocarbon mixture that, when vaporized, can create an explosive mixture with air [22]. The discovery of naphtha is attributed to John Taylor, an English mining engineer who patented a process in 1815 for converting animal oil into oil-gas [23]. This innovation disrupted the coal gas monopoly, leading to a competitive market. The novelist Philip Meadows Taylor noted this rivalry in his 1823 book, *A Memoir of the*

Family of Taylor of Norwich*, stating, "Five years after the discovery, in 1823, the battle of the gases took place; but the combat was unequal. Large companies were formed, and substantial sums were invested in manufacturing coal gas. Applications were made to the House of Commons for charters, and investigation committees were formed; the Taylors had to stand alone against the combination of wealthy promoters" [24],[25]. He remarked that the competition was unbalanced, with oil-gas capturing only about 20% of the market – partly due to its higher cost and increased danger compared to coal gas. Despite occasional accidents involving both types of gas, Philip Taylor – John's brother and a civil engineer – developed a method for lighting private and public buildings using oil-gas lamps [26]. The technological pinnacle of gas lamps was achieved by introducing lamps featuring the Welsbach mantle, commonly known as the gas mantle. This groundbreaking innovation is attributed to Austrian chemist and inventor Carl Auer von Welsbach [27],[28]. He is known for several significant discoveries in chemistry, including identifying lutetium. However, his contributions to lighting technology are equally noteworthy. In addition to the gas mantle, he developed the metal-filament light bulb and the lighting flint, which we still see in lighters today. Welsbach's famous motto, "plus lucis" [29], translates to "more light," reflecting his dedication to this field [30].

The patent for the initial version of the gas mantle was registered on September 23, 1885. Welsbach named this development "Auerlicht," which continues to be used today and means "outer light." The mantle comprised 60% magnesium oxide, 20% lanthanum oxide, and a compound containing 20% yttrium oxide. He referred to this mixture as Actinophor [31].

Magnesium oxide is well-known for its brightness when burned, while lanthanum is an excellent catalyst for producing highly resistant glass. Yttrium, meanwhile, is used for creating phosphorescent materials in technologies such as LEDs and is also a crucial element in superconductors, although it can pose health risks.

To prepare the mantle, Welsbach soaked guncotton in Actinophor and heated it, causing the cotton to reduce to ash. This left a solid ash that glowed brightly with a greenish hue. Despite this technological breakthrough, the initial gas mantle did not gain widespread popularity.

Five years later, in 1890, Welsbach introduced a further developed version of the gas mantle, created in collaboration with his colleague Ludwig Haitinger. This new version contained 99% thorium dioxide and 1% cerium(IV) oxide. Thorium dioxide, a by-product of producing lanthanides and uranium, has one of the highest melting points among chemical substances at 3300 °C; only a few elements, like tungsten, with a melting point of 3422 °C, surpass it. However, all thorium compounds are radioactive and lack stable isotopes, posing potential health risks.

Today, cerium(IV) oxide has two main applications: polishing and decolorizing glass. The updated material in the second gas mantle version was less fragile, and the emitted light shifted from a greenish

tint to a warm white hue. This second version eventually gained popularity, with The Coleman Company in America commencing production of the new gas mantle lamps. Today, Coleman is recognized as one of the world's largest camping equipment manufacturers.

Due to a lawsuit arising from concerns about radiation, Coleman later replaced thorium with yttrium in their production process. Studies on the radiation hazard of this technology were brought to light during court proceedings, leading the company to make changes [32].

Gas lamps continued to be used for street lighting until the early 20th century when emerging technologies began to replace them. However, some cities still operate these lamps today due to their historical and nostalgic appeal. As of 2022, Berlin had the highest number of operational gas lamps, with nearly 23,000 still in use.

3.4. Arc lamp, the dawn of electricity

The next generation of streetlamps marked a significant shift from the previous technology, which relied on fire in some form, to a new foundation based on electricity. This innovation was fundamental to modern society, and remains so today. Electricity plays a crucial role in all aspects of lighting, and the advantages of using electricity over fire-based technologies were quickly recognized.

While electricity was known in ancient times, it was primarily recognized in its naturally occurring forms, the most common being lightning during storms and documented encounters with various species of electric fish. Ancient texts also indicate an awareness of the hazardous effects of electricity on humans. The Greeks had a basic understanding of electrostatics. However, this level of familiarity persisted until the 16th century, as people had limited experience with electricity beyond what they observed in nature.

Interest in electricity grew in 1600 when English physicist William Gilbert, a natural philosopher and personal physician to Queen Elizabeth I, published his scientific work titled "De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure". This book drew inspiration from the earlier works of Robert Norman, a mariner and compass builder credited with discovering magnetic inclination (the vertical angle of the Earth's magnetic field). Gilbert focused primarily on the properties of magnets and terrestrial magnetism, but he also conducted experiments related to electrostatics. He introduced the New Latin term "electricus," meaning "like amber," to describe the attractive properties of amber. His experiments explored the attraction created by electric charges. He continued this line of inquiry by discussing static electricity and named the effect related to amber, derived from the Greek word "electron" as an electric force. He also invented the first device for detecting electric charge, known as the electroscope, referring to it as the versorium [33].

In 1646, the English polymath Sir Thomas Browne first used the terms "electric" and "electricity" in his encyclopedia, "Pseudodoxia Epidemica, or, Inquiries into Very Many Received Tenets and Commonly

Presumed Truths". This marked the first printed appearance of these words [34].

Significant experiments in electricity are associated with the American polymath Benjamin Franklin, one of the signers of the Declaration of Independence and the sixth president of Pennsylvania [35]. Franklin was the first to differentiate between electric charges, labeling them positive and negative [36]. He also discovered the principle of charge conservation [37]. To demonstrate the dangers and potential applications of electricity, he organized a dinner party in 1749 where he electrocuted a turkey using an electric spit [38], later claiming that "the birds killed in this manner eat uncommonly tender" [39]. Some of his instruments are now part of the Harvard Collection of Historical Scientific Instruments, on display at the Harvard University Science Center. His most famous experiment occurred in 1752, when he demonstrated that lightning is a form of electricity by flying a kite during a storm and successfully conducting electricity from the kite to the ground. He reported his findings in *The Pennsylvania Gazette* on October 19, 1752 [40]. His experiments ultimately contributed to the invention of the lightning rod, a crucial safety device still in use today [41]. In the 19th century, significant discoveries and inventions in the field of electricity laid the groundwork for its later use. One crucial invention was the electric battery, introduced in 1800 by Italian physicist and chemist Alessandro Volta [35]. This discovery was significant because it demonstrated that, contrary to previous beliefs that only certain animals could produce electricity, electricity could be generated chemically and stored [42].

Another significant development was the work of Danish physicist Hans Christian Ørsted and French physicist André-Marie Ampère, who explored the relationship between electricity and magnetism [43]. Building on their findings, English natural philosopher Michael Faraday created the first electric motor in 1821 [44]. Meanwhile, German physicist and mathematician Georg Simon Ohm established Ohm's Law, a fundamental principle of electricity, based on his research with Volta's battery [45]. The theoretical foundation was further refined by Scottish mathematician James Clerk Maxwell, who developed the theory of electromagnetic radiation that is still in use today. Maxwell's equations and the Lorentz force law describe the behavior of electromagnetic radiation, encompassing magnetism, electricity, and light as different forms of the same phenomenon [46].

These experiments, discoveries, and inventions were essential for electricity to become a cornerstone of modern civilization. With the development of electrical theory, engineering adapted this new knowledge, leading to revolutionary advancements in numerous fields, particularly in lighting technology, which has become a major area of electricity's application.

The practical implementation of electricity in lighting is first credited to British chemist and inventor Sir Humphry Davy, who served as the 23rd President of the Royal Society. He made two significant contributions to lighting technology. His first achievement was the

safety lamp, known as the Davy lamp, introduced in 1815. This lamp created a safe solution for miners by reducing the risk of explosion-related accidents; the combustion area was isolated from the environment with a mesh screen.

The precursor to Davy's second major achievement was the work of Russian physicist Vasily Vladimirovich Petrov, who discovered the electric arc effect in 1802. In his detailed presentation of voltaic pile experiments, Petrov suggested that the stable electric arc could be used for artificial lighting as well as for welding and metal melting. Building upon Petrov's work, Davy constructed what was then considered the most powerful electric battery in 1802, which allowed him to drive a large current through a thin platinum plate [47]. Although this early design was not durable enough to produce convincing brightness, it played a pivotal role in lighting technology as the first practical application of electricity in this field, often regarded as the first incandescent light.

Continuing to refine his work, in 1806, Davy presented a new and more powerful construction to the Royal Society in London, which produced light through a stable electric arc formed between two carbon rods. This invention marked the initial development of arc lamps, specifically carbon electrode lamps. In these lamps, the electrodes were only insulated from the environment by a glass dome. To start the lamp, the electrodes had to touch to establish electrical contact, after which they could be slowly pulled apart, allowing an electric arc to form between the tips.

During operation, a significant amount of heat was generated at the tips of the electrodes, causing the carbon to gradually vaporize. When this carbon vapor interacted with the electric arc, it emitted bright light. However, as the electrodes shortened over time, continuous adjustments were necessary to maintain the arc [48]. Initially, these adjustments were made manually, but various automated methods were later developed to address this task. One popular solution involved using an electromagnet built around the electrodes. The current generating the magnetic field of the coil fluctuated depending on the distance between the electrodes; when they touched, a quasi-short circuit occurred, triggering the mechanism to reposition them automatically [47]. In the field of street lighting, the first lamp to utilize arc technology was known as the Yablochkov candle, or electric candle, invented by Pavel Nikolayevich Yablochkov, a Russian electrical engineer and businessman, in 1876. The Yablochkov candle differed from earlier arc lamps in that its carbon electrodes were placed in parallel, close together, and isolated from one another, mainly using plaster. Initially, the ends of the electrodes were connected with carbon paste. When the lamp was switched on, the paste burned out quickly, severing the connection and allowing an electric arc to form. During operation, the insulation surrounding the electrodes burned along with the electrodes, maintaining the correct distance between them. This design eliminated the need for continuous mechanical alignment, simplifying the lamp's structure.

The operating time of the Yablochkov candle was approximately two hours, meaning that the electrodes had to be replaced several times during one night. A significant drawback of this technology was that the lamp could only be ignited once. In a later, improved version, a metal powder solution replaced the carbon paste, allowing the lamp to be restarted at any time [47],[49].

Another challenge associated with this technology was how to power the lamp. The first versions were powered by direct current using the Gramme machine, invented by Belgian electrical engineer Zénobe Gramme, who presented it in 1871 at the Paris Academy of Sciences. This was the first generator capable of meeting industrial demands for electricity. However, using direct current had a disadvantage: one electrode wore down twice as fast as the other, causing the distance between them to increase until the electric arc was extinguished. This problem was initially addressed by making one electrode thicker than the other, but the ultimate solution was to use alternating current, which consumed the electrodes evenly.

The first public demonstration of the lamp took place on April 15, 1876, in London. The City of Los Angeles acquired four Yablochkov candles in the same year. In 1877, the Marengo Hall in Paris installed eighty of these lamps, which, although not used for street lighting, significantly contributed to the technology's publicity since it was a high-profile venue attracting many visitors.

The Yablochkov candle was first used for street lighting on May 30, 1878, during the festive opening of the Paris Universal Exposition, near the avenue de l'Opéra and the Place du Théâtre Français, where sixty-eight lamps were installed [50],[51]. The new lamps were so successful that in December of that year, London ordered lamps for installation along the Thames Embankment and the Holborn Viaduct [52]. The lamp quickly gained popularity worldwide, with over one hundred thousand units in the United States by the end of the 19th century.

The technology's success may be attributed to two significant advantages. First, compared to earlier technologies, the arc lamp produced higher light output, allowing a single fixture to illuminate a much larger area and providing greater brightness, thereby enhancing public safety. Second, production costs were low, and the lamp's relatively simple design made mass production feasible. Reports indicate that around 8,000 Yablochkov candles were produced daily in France at the peak of its popularity.

Like its carbon arc predecessors that relied on fire (oil, gas), the Yablochkov candle was not without hazards. During operation, it released carbon monoxide due to coal combustion and emitted a significant amount of UV radiation. Its high operating temperature and frequent sparks also made the equipment highly flammable, as with earlier technologies [47].

A later version of arc technology is the Vortek water-wall plasma arc lamp, developed in 1975 by David Camm and Roy Nodwell, PhD students. This lamp was capable of over 300 kW of power, earning entries in the

Guinness Book of World Records in 1986 and 1993 [53]. A more advanced version of arc technology, known as gas-discharge lamps, is still in use today. These lamps serve various purposes, such as providing a high-intensity ultraviolet light source in IMAX projectors and being used in modern streetlights, which we will discuss later. The current form of gas-discharge lamps differs from earlier versions in that the electrodes are made of durable metal and are housed within a gas-filled dome, typically made of xenon-filled gas [47].

3.5. Incandescent light bulb, widely known

In parallel with the development of arc lamps, research was already underway on incandescent lights, as previously mentioned in connection with Humphry Davy's inventions. Although this technology was adopted somewhat later, it ultimately replaced arc lamps in most contexts, including public lighting, while arc lamps continued to be used in industrial settings for some time. The history of light bulbs is more diverse and complex than that of earlier technologies, mainly because this period saw significant advancements in electricity, lighting, and technologies integral to modern life. The First Industrial Revolution had already occurred by this time, introducing numerous innovations into people's lives. The world was now entering the era of the Second Industrial Revolution, marked by numerous inventors and innovations.

The initial form of incandescent lamps can be traced back to Humphry Davy's earlier work, which involved creating light by passing a high current through a thin platinum plate. Although this idea did not gain much traction, it laid the groundwork for the development of arc lamps. Other inventors continued to explore Davy's idea. One notable figure was James Bowman Lindsay, a Scottish inventor often regarded as a pioneer of the light bulb and telegraphy. However, documentation of his contributions to the development of light bulbs is limited. In July 1835, at a public event in Dundee, Scotland, he demonstrated a constant electric lamp that, according to his claims, enabled him to read a book in the dark from approximately half a meter away.

Belgian photographer and inventor Jean-Baptiste-Ambroise-Marcellin Jobard made a significant advancement in light bulbs in 1838 by isolating carbon fiber in a vacuum chamber [54]. This innovation addressed a critical drawback of carbon fiber – its short lifespan caused by oxidation when burned in the air. In a vacuum, however, the lifespan of the fiber was greatly extended as it was shielded from air exposure.

British astronomer and chemist Warren De la Rue, known for his early stereoscopic photographs of the Moon and Sun, contributed his own solution in 1840 [55]. Instead of carbon fiber, he employed a platinum coil, which had a higher melting point and could withstand greater temperatures. This allowed for higher amperage, resulting in increased luminous output, but also created a cooler color temperature. However, the high cost of platinum limited its commercial viability [56]-[58].

The first patent for an incandescent lamp was registered in 1841 by British inventor Frederick de Moleyns. His lamp utilized carbon powder placed between two platinum plates, but this solution also did not reach the market [59],[60]. Over the next few years, several additional patents were filed, yet they failed to gain commercial traction for two primary reasons: the wire used could not withstand sustained high temperatures, and vacuum technology was still in its infancy. These factors contributed to the short lifespan and inadequate brightness of early lamps, which were further hindered by hoods that quickly blackened due to imperfect vacuum technology.

Russian electrical engineer and inventor Alexander Nikolayevich Lodygin made further advancements in this field. On July 11, 1874, he was awarded a patent for a light bulb design from 1872 that featured two carbon filaments separated by a space filled with nitrogen gas. This innovative design allowed the carbon filaments to be used sequentially. Lodygin was honored with the Lomonosov Gold Medal by the Petersburg Academy of Sciences that same year. However, in 1884, he fled to the United States due to his association with the Narodniks socialist movement, which had been targeted following an assassination attempt against Emperor Alexander II of Russia. In the U.S., Lodygin continued to refine his light bulb technology and successfully patented several of his new developments, including bulbs with iridium, rhodium, and molybdenum filaments, as well as the first tungsten filament bulb [61]-[63].

On July 24, 1874, Henry Woodward and Mathew Evans filed a patent for a carbon filament incandescent lamp encased in a nitrogen-filled cylinder rather than a vacuum [64]. Lacking the funds to develop it into a final product, they sold the patent rights to American inventor Thomas Alva Edison under US patent number 181,613. Edison perfected the design and publicly demonstrated his light bulb in Menlo Park on December 31, 1879 [65]. In the following years, he also worked on improving the manufacturing process for carbon filaments in incandescent lamps [35].

In 1881, Italian inventor Alessandro Cruto developed a new filament that was more efficient than Edison's. Unlike the yellowish warm white light produced by Edison's bulb, Cruto's filament emitted a much colder and whiter light. This was the first synthetic filament, made from a thin, super-pure graphite created through the sublimation of platinum at high temperatures.

Another key figure in the history of light bulb development was Croatian engineer Franjo Hanaman. Along with his assistant, Austro-Hungarian chemist Alexander Friedrich Just (Just Sándor Frigyes), he invented the world's first tungsten filament light bulb, for which they received patents in Hungary and later in the U.S. in 1904. This technology was significantly more efficient than earlier carbon filament designs, as tungsten filaments could withstand higher temperatures and last longer. However, they were fragile, a problem that American physicist William David Coolidge addressed

through his drawn tungsten design while working at General Electric [66].

Irving Langmuir, a Nobel Prize-winning American chemist and physicist, and his colleague Lewi Tonks, an American quantum physicist, further advanced light bulb technology with their discoveries. One significant finding was that filling the bulb with a noble gas instead of a vacuum greatly extended the lifespan of the tungsten filament. Additionally, they discovered that using a coiled filament design, rather than a straight connection between electrodes, increased the lamp's efficiency by maximizing the filament's surface area. A larger surface area results in greater light emission since more of the filament is involved in the glow.

In subsequent years, there were additional refinements in light bulb technology to make them more efficient and durable. However, these developments represent the main historical milestones in the evolution of lighting, with some of this technology still found in outdated households today.

The first incandescent streetlights were installed on the main street of Chesterfield, England, on February 3, 1879, for just one night. As light bulbs became more commercially available, incandescent lamps gradually replaced arc lamps worldwide. Today, incandescent lamps are still used in street lighting in some areas, such as parts of Los Angeles and San Francisco, primarily because infrastructure constraints, such as the series connection of lamps, which make switching to modern technology costly.

3.6. Gas-discharge lamps are still widely used today

The technology that emerged alongside incandescent lamps and has since largely replaced them in the market is known as gas-discharge lighting, which falls into three main categories: low-pressure discharge lamps, high-pressure discharge lamps, and high-intensity discharge lamps. Low-pressure gas-discharge lamps were primarily used in households and can still be found in everyday life. On the other hand, high-pressure discharge lamps have become the standard for street lighting, making them the most common form of public illumination today. High-intensity gas discharge lamps, meanwhile, are mainly used in specialized applications, such as projectors, as mentioned in the chapter on arc technology.

The motivation behind developing gas-discharge lamps can be traced back to the work of Sir Humphry Davy. It is essentially tied to variations of the first lamp mentioned in the chapter on arc lamps. Some innovators envisioned a future with Davy's second lamp variation, leading to the creation of the incandescent lamp, while others recognized considerable potential in the first variation and pursued it for further testing. When considering the motivations for developing incandescent lamps, cost-effectiveness stands out; the aim was to make artificial lighting accessible to as many people and places as possible, which required both quantity and affordability. Conversely, those who focused on gas-

discharge lamps were driven by the quest for greater luminous efficiency, as discharge lamps offer significantly better efficiency than incandescent lamps. However, their complexity and sophistication result in higher costs.

The first generation of gas-discharge lamps is represented by the Geissler tube, invented in 1857 by Johann Heinrich Wilhelm Geißler, a German glassblower and physicist [67]. These lamps consist of two electrodes positioned at the ends of a partially evacuated glass tube, which contains a small amount of noble gas (such as neon, argon, or xenon) along with conductive liquids and other ionizable materials, such as sodium. In some cases, the tube may contain ordinary air. When a high voltage is applied to the electrodes, the electric field causes the gas between them to emit electrons, resulting in ionization and the creation of plasma. This plasma forms a conductive path between the electrodes, enabling current to flow. Meanwhile, ions recombine with electrons escaping from the cathode, producing electromagnetic radiation in the form of light. Maintaining a rarefied environment inside the tube is crucial; if too much air were present, air molecules would absorb the electrons, preventing them from reaching the anode and interrupting the ionization process essential for light generation. The color of the emitted light varies depending on the ionization material used in the tube, allowing for the production of multiple colors [68].

In low-pressure discharge lamps, the internal pressure is approximately one-hundredth of the surrounding atmospheric pressure, whereas high-pressure discharge lamps operate at pressure levels similar to the ambient atmosphere. Consequently, the Geissler tube falls under the category of low-pressure discharge lamps [69],[70].

Most gas-discharge lamps also require an ignition circuit to provide the high-voltage pulse needed to initiate ionization. This may necessitate the use of current-limiting elements, such as a choke coil. The Geissler tube served as the foundation for various subsequent light sources, including neon tubes, xenon flash lamps, plasma globes, sodium-vapor lamps, and mercury-vapor lamps, demonstrating the significant impact of Geissler's invention. Due to its wide range of applications, it is worth mentioning the contributions of German mathematician and physicist Julius Plücker. He conducted extensive experiments with Geißler's gas-discharge tube, which were instrumental in the discovery of the electron in 1897. The neon tube is linked to the work of French engineer and inventor Georges Claude. In 1902, he developed an efficient system for liquefying air, now known as the Claude system, which enabled the industrial production of liquid nitrogen, oxygen, and argon. Neon gas was one by-product of this process, playing a crucial role in subsequent developments [71].

In the same year, Claude and his business partner Paul Delorme founded the Paris-based company Air Liquide, which remains significant in the global production of liquefied chemicals. Claude also proposed utilizing the generated neon gas, aiming to make use of all by-products from the liquefaction process. He created

a device similar to a Geissler tube filled with neon gas, thus inventing the first neon tube. Claude publicly presented his invention in 1910 at the Salon de l'Automobile et du Cycle and patented it on March 7 of the same year. This patent was connected to advancements in purifying the filling gas and extending the lifespan of the electrodes. This technology evolved into what we know today as neon light advertisements. However, Claude faced legal consequences after World War II for supporting the Germans, resulting in his imprisonment in 1945.

Currently, the most prominent versions of gas-discharge lamps are metal-vapor-based, with sodium and mercury being the most commonly used metals. These lamps continue to serve as key components in public lighting. Sodium-vapor lamps are particularly prevalent because of their favorable light characteristics. There are two types of sodium-vapor lamps: low-pressure (LPS) and high-pressure (HPS). Both types emit a yellowish, warm color temperature. LPS lamps have a high light-utilization factor but produce monochromatic light at 589 nm, which distorts color perception. In contrast, HPS lamps emit light across a broader spectrum, although their color rendering index is also subpar. The first generation of LPS lamps was introduced in the 1920s, while the HPS variant was first demonstrated in 1959 and launched commercially in 1965 with a 400-Watt version. Compared with older technologies, both HPS and LPS lamps offer higher performance, greater luminous flux (exceeding 42,000 lumens), and an average lifespan of 24,000 hours [72].

Philips, a leading manufacturer of LPS lamps, announced in 2017 that it would discontinue these lamps due to their outdated technology and declining demand. The last LPS lamp was produced at the company's Hamilton factory on December 31, 2019. Despite this, many LPS and HPS lamps are still in operation today.

To quantify the number of such lamps in major cities, the Budapest Lighting Master Plan includes a survey conducted before 2020, which revealed 178,270 light fixtures in the capital [73]. Out of these, 156,132 are sodium lamps, while the remainder comprises fluorescent, metal halide, mercury, and LED lamps. The city aims to implement large-scale modernization by 2030, focusing on reducing light pollution and energy consumption.

A striking example of public lighting differences can be seen in Berlin, where the historical remnants of the Iron Curtain affect lighting today. Satellite images show the city's eastern part glowing yellow due to nearly 40,000 sodium lamps still in operation, while the western part shines with fluorescent and LED lights. The gap between the two regions is gradually closing thanks to ongoing modernization efforts in the eastern part. Comparing satellite images from 2012 with those from today clearly illustrates the progress in upgrading the city's public lighting.

In Greater Noida, India, there are 54,000 HPS lights. In 2021, the city launched a replacement tender to convert all HPS lights to LED lights in the coming years to reduce energy consumption.

Table 1: Luminous efficiency of different technologies [75]-[77]

Technology	Luminous efficiency (lm/W)	Lifetime in hours
Candle	0.16	< 24
Oil lamp	0.21	< 5500
Gas lamp	2	< 7500
Carbon Arc lamp	12	< 100
Incandescent	15-20	< 1000
High-Pressure Sodium	80-100	12.000-16.000
LED	80-160	50.000-100.000

4. State of the art in lighting technologies

Today, the most advanced lighting technology is the light-emitting diode, commonly known as an LED. These devices are ubiquitous, appearing in various applications ranging from consumer electronics, such as mobile phones, TVs, monitors, and projectors to medical equipment. Additionally, they play a significant role in general lighting and street-lighting solutions [74].

The success of LEDs can be attributed to several key properties: energy efficiency, flexible applications, customizable parameters, affordability, and long lifespan. These characteristics allow LEDs to be used in diverse settings, from pixel-level lighting to dimmable room lights and high-performance stadium lighting. The lifetime and luminous efficiency of the different lighting technologies are detailed in Table 1.

LEDs represent a significant advancement in semiconductor technology. They consist of two layers: a p-type semiconductor and an n-type semiconductor, separated by a thin boundary layer. When an electrical source is connected to the electrodes of these layers, a positive charge accumulates in the p-type layer, while a negative charge builds up in the n-type layer. This charge accumulation initiates a recombination process at the boundary layer, where the positive and negative charges combine, releasing energy in the form of photons [78]. The energy level of these emitted photons determines the color of the light perceived, which depends on the specific semiconductor material and any "impurities" present, as indicated in Table 2.

Depending on the materials used, the emitted narrow-spectrum light can fall into the ultraviolet (UV), visible (including blue, red, and green), or infrared (IR) ranges. Producing white light is slightly more complex and can be achieved in two ways. The first method, primarily used for dimmable LEDs, involves creating white light by mixing blue, green, and red LEDs. The second method employs a lens made of a blue LED that is coated with a fluorescent material; this material

Table 2: Main properties of LEDs [79],[80]

Color	Material	Wavelength (nm)	Forward voltage (V)
Ultraviolet (UV)	Indium gallium nitride, Aluminum gallium nitride	370-400	3.1-4.4
Blue	Indium gallium nitride, Gallium nitride, Zinc selenide, Sapphire, Silicon carbide	430-505	2.5-3.7
Green	Gallium nitride, Aluminum gallium phosphide	550-570	1.9-4.0
Red	Aluminum gallium arsenide, Gallium phosphide, Gallium arsenide phosphide	630-660	1.6-2.0
Infrared (IR)	Gallium arsenide, Aluminum gallium arsenide	850-940	<1.2

absorbs blue light and re-emits it across the visible white-light spectrum.

The evolution of LEDs can be divided into three major generations, each introducing innovations that enhanced their efficiency and performance [74]-[78].

The first generation of LEDs emerged commercially in 1962 and lasted until the 1980s. Texas Instruments released the first commercially available LED, known as the SNX-100 model, which was made from GaAs semiconductor material. This LED emitted light at a wavelength of 890 nm in the infrared range, limiting its application to optical communication. However, the demand for LEDs that emit light in the visible spectrum prompted further developments.

In 1961, J. W. Allen and R. J. Cherry at the Services Electronics Research Laboratory (SERL) in Baldock, UK, introduced the first visible red LED [82]. Shortly thereafter, M. George Craford invented the first yellow LED and significantly increased the brightness of the earlier red LED design.

At that time, LED technology was considered expensive, with units priced at around \$200 due to its novelty and complexity compared to previous technologies. As a result, first-generation LEDs had limited practical applications in the 1960s. However, their availability and affordability improved significantly by the 1980s. Some of the first companies to manufacture LED products included Hewlett-Packard (HP) and Monsanto in the late 1960s. Initially, first-generation LEDs were used primarily as indicator lights, but by the

Table 3: Luminous efficiency of LEDs over the years [74]-[85]

Year	Luminous efficiency (lm/W)	Note
2009	105	CREE XP-G series
2010	140	Nichia 19 series
2011	231	Cree's prototype
2014	303	Cree's prototype
2017	200	Philips's consumer LED
2018	223	Samsung's consumer LED

end of this generation, they were also utilized in seven-segment displays, such as those found in the Texas Instruments TI-30 calculator [83].

Models developed and marketed from the 1990s to today are considered the second generation of LEDs. One of the primary differences between these LEDs and earlier generations is their significantly higher brightness. This generation is characterized by the widespread use of LEDs across various applications. Around 1993, high-performance blue LEDs were introduced, which eventually led to the development of Blu-ray technology, thanks to the work of Shuji Nakamura, Isamu Akasaki, and Hiroshi Amano. Shuji Nakamura was awarded the Millennium Technology Prize in 2006 for his groundbreaking contributions to blue LEDs. The three of them also received the Nobel Prize in Physics in 2014 for their achievements.

Following the development of blue LEDs, researchers and engineers immediately began working on white LEDs [84],[85]. The creation of high-performance white LEDs was crucial, making it possible to use this technology in general and public lighting. Before white LEDs were developed, white light could only be produced by mixing the three primary colors, which resulted in a narrow spectrum and poor color-rendering index. The first high-performance white LED, which set a record with an output of 303 lm/W, was introduced by Cree in 2014, establishing the company as one of today's leading LED manufacturers. Meanwhile, other significant players, such as Osram, Samsung, and Toshiba, initiated a technological revolution in the entertainment industry, lighting technology, and many IT sectors, utilizing LEDs in applications such as display backlighting, projectors, and car headlights, as well as home and public lighting.

The third generation of LEDs is currently available on the market and represents the future of this technology. This generation embodies the state-of-the-art developments in the field. The main characteristics of new-generation LEDs include materials and production technologies that prioritize high performance, energy efficiency, and environmental sustainability. Among the most notable new-generation LEDs are organic light-

emitting diodes (OLEDs). OLEDs are referred to as "organic" because they use organic compounds in their electroluminescence, which emit light when an electric current is applied. Several types of OLEDs are commonly found in consumer electronics, such as smart TVs and smartphones. These devices enable the creation of displays that offer excellent image quality and color accuracy, as seen in LG's smart TVs. One of the best-known types of OLED is AMOLED (active-matrix organic light-emitting diode), introduced by Samsung in 2010, which the company has continued to use in its TV and phone displays.

Today, LED technology has become standard in various electronic products with display capabilities. Moreover, considering climate change and other economic factors, the adoption of LEDs for general and public lighting is anticipated to grow because of their energy efficiency, even though it is not yet universal. Modern homes now typically include LED lights both indoors and outdoors. The automotive industry reflects similar trends, as LED headlights have become standard equipment in new cars, regardless of whether they are budget-friendly or high-end vehicles.

In discussions about LEDs, Haitz's law is often mentioned, which predicts a relationship similar to Moore's law. According to Haitz's Law, there will be an "exponential rise in light output and efficiency of LEDs over time" [85]. The validity of this prediction is illustrated in Table 3. Today, LED lighting fixtures are available in a wide variety of designs and performance options. The shift from older technologies to this modern and energy-efficient solution is rapidly gaining traction in both residential and public lighting [86],[87]. Many established companies, such as Philips, Samsung, Osram, and Cree, have been prominent in the LED market for years, but numerous new and emerging businesses are also entering this field.

One of these companies is Hofeka Ltd., founded in 1888 and Hungary's leading developer and manufacturer of street-lighting fixtures. Hofeka Ltd.'s product range includes LED lighting fixtures, decorative and public lighting equipment, outdoor, sports, and industrial lighting solutions, as well as Smart City innovations.

In any developed country, it is common to find at least one company with a product portfolio similar to Hofeka Ltd.'s. This is noteworthy because companies in developed nations often focus primarily on meeting domestic needs, striving to make the transition to LED technology as quick and seamless as possible while considering specific local requirements, such as design aesthetics. This localized approach contributes to a smaller ecological footprint, as most products are transported within the country, resulting in lower emissions than those associated with shipping products internationally.

It is important to highlight that these companies are not completely neglecting export opportunities; rather, their primary focus is on addressing domestic demands.

5. Further trends in public lighting development

The lighting technology industry is currently focused on the future of LEDs. This advancement can be categorized into two major trends: increasing energy efficiency [88],[89] and adding innovative smart functions to light fixtures [90]-[94].

Enhancing energy efficiency is crucial because it can help reduce the environmental impact associated with electricity production [95],[96]. There are various approaches to address this issue. One approach involves further improving the efficiency of LEDs, while another focuses on integrating environmentally friendly alternative energy sources into lighting fixtures. Solid-state lighting technologies, classified as ultra-efficient solid-state lighting, currently achieve efficiencies greater than 70%, with some even exceeding 80% [97]. A popular approach to improving energy efficiency is to equip LED streetlights with solar panels and batteries, enabling them to operate independently of grid power for most of the year as autonomous systems that utilize clean energy.

The second trend involves incorporating innovative functions into lighting solutions. These functions often rely on various sensors, such as those for temperature, humidity, twilight, illumination, and rain. By using the data collected from these sensors, lighting can be adjusted to suit external conditions, such as by modifying lamp brightness or adjusting the color temperature accordingly.

6. Discussion and conclusion

The need for artificial lighting is nearly as old as human civilization itself; even in ancient times, the light from the moon and stars was insufficient to illuminate the darkness of night. While technology has evolved over time, the fundamental goal has remained the same: to provide light during the night to enhance people's safety. Initially, there was no public lighting as a collective good, but this changed over time. By the end of the Middle Ages, public lighting began to serve the public interest. When examining the development of artificial lighting, we can see that technological advancements started slowly but accelerated significantly around the Industrial Revolution, and this progress continues today. We transitioned from fire to oil and gas lamps, leading into the Second Industrial Revolution when electricity emerged as one of humanity's greatest achievements. This breakthrough paved the way for entirely new technologies, including arc lamps and, later, incandescent lamps. Building on the innovations from these earlier technologies, we eventually reached gas-discharge lamps, which are still widely used today, such as low-pressure sodium (LPS) and high-pressure sodium (HPS) lamps. Today, the focus is on LED technology, which is gradually replacing many of the gas-discharge lamps still in use. While we cannot predict what

revolutionary solutions may emerge after LEDs, we can anticipate experiencing the excitement that our predecessors felt when they embraced new and radically different technologies. However, we will likely have to wait longer for such advancements, as LEDs are expected to remain in use for some time, and we have likely not yet fully tapped their potential because this technology is still relatively young and ripe for further development.

If the evolution of lighting technology could be summarized in one word, it would be "efficiency." A closer examination of lighting technologies reveals that newer-generation lamps typically offer better light utilization and more favorable energy consumption than their predecessors, making them more cost-effective.

Future developments in lighting technology will continue to emphasize energy efficiency. Alongside advancements in electrical engineering, research and innovation in lighting systems are becoming increasingly important. The concept of Human-Centric Lighting (HCL) is gaining significance, and informatics is beginning to play a role through the use of various artificial intelligence tools to enhance control technologies and theoretical frameworks. Future research should focus not only on technological development but also on exploring the applicability of these technologies and their effective implementation.

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